Main feature

Air quality indices and cleanroom ventilation equations, and their application in a cleanroom HVAC system, part one: theoretical considerations

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Abstract

This, the first part of a two-part paper summarizes current understanding of air quality indices and cleanroom ventilation equations and their use in a cleanroom heating, ventilation and air conditioning (HVAC) system. The equations for air quality indices, including the contaminant removal effectiveness index (CRE) and the air change effectiveness index (ACE) are reviewed, based on particles rather than gases, and dispersion rates from personnel and machinery are examined. The cleanroom ventilation equations, together with the air quality index and the dispersion rate of particles, are then used to calculate the minimum air change rate (ACR) that is required in non-unidirectional cleanrooms to achieve less than the maximum specified concentration of airborne particles. The second part of the paper will describe the experimental work carried out by EECO2 Ltd.

Introduction

Cleanrooms are widely employed in high-technology manufacturing, as in pharmaceutical, semiconductor and optoelectronic manufacturing, to meet the stringent requirements of high air cleanliness levels in the processing environment [1]. The high-technology manufacturing environment is based on a series of cleanrooms whose airborne particulate levels are controlled. As defined by the international cleanroom standard, ISO 14644-1 [2], a cleanroom is a “room within which the number concentration of airborne particles is controlled and classified, and which is designed, constructed and operated in a manner to control the introduction, generation and retention of particles inside the room”. Cleanroom air cleanliness classifications are specified according to the use of the cleanroom [3]. There are two main standards by which pharmaceutical cleanrooms are classified: EU GMP [4] and ISO 14644 [2]. These standards categorize cleanrooms based on the maximum permitted particle concentrations as measured by counting the number of particles in one cubic meter of air. The particle concentration is controlled by the heating, ventilation and air-conditioning (HVAC) system which circulates air in the cleanrooms with a relatively high air change rate (ACR) [5].

Among building energy services, HVAC systems consume the most energy and account for about 10 - 20% of final energy use in developed countries [6]. Energy consumption due to the maintenance of environmental conditions by means of HVAC systems accounts for 50% - 70% of the total energy consumption for pharmaceutical manufacturing [7]. The provision of the supply airflow rate contributes significantly to the energy consumption of a cleanroom [8]. The reduction of the supply airflow rate gives a significant reduction of the overall energy use, with the associated reductions in cost and carbon footprint. Particles of different sizes behave differently as air moves through a room with, as a generalization, particles >1µm tending to settle out and particles <1µm tending to remain in the airflow. Selection of the airflow patterns is a major step in cleanroom design. There are three different types of airflow in a cleanroom:

1) Unidirectional airflow

Unidirectional airflow (UDAF) is defined in ISO 14644-4 [9] as “controlled airflow through the entire cross section of a clean zone with a steady velocity and approximately parallel airstreams.” A note adds “This type of airflow results in a directed transport of particles from the clean zone.” It is also specified as ≤14° from perpendicular when performing airflow parallelism [10]. Unidirectional filtered airflow is used for class ISO 5 and cleaner [9]. Particles are swept away from the critical zones and the airflow velocity is therefore critical. It has been shown that velocities as low as 0.3 m/s provide low concentrations of airborne contamination in normal levels of occupancy and activity, in unidirectional rooms.

2) Non-unidirectional airflow

Non-unidirectional airflow is defined in ISO 14644-4 [9] as “air distribution where the supply air entering the clean zone mixes with the internal air by means of induction”. ISO Class 6 through 9 cleanrooms are recommended to use non-unidirectional airflow designs [9]. The concentration of particles is diluted by mixing with the filtered supply air and the mixed air is then removed from the critical zone in the exhaust air. This process is ACR dependent. For non-unidirectional airflow cleanrooms, the supply air rate, and correspondingly the ACR, needs only to be sufficient to effectively dilute the particles generated, known as the source strength, to an acceptable concentration.

3) Mixed airflow

Mixed airflow is described in ISO 14644-4 [9] as combining both unidirectional and non-unidirectional airflow in the same room. It is well understood that higher airflow rates in the form of volume for non-unidirectional flow (dilution) and velocity for unidirectional flow (displacement) lead to a lower airborne contamination level [8]. Regulations and expected practice for both cleanroom types have dictated airflow rates that in some cases are excessive.

Air quality indices

Increased ventilation efficiency could be a significant way to decrease the amount of energy used to achieve effective ventilation of the interior spaces of buildings [11]. Ventilation efficiency is evaluated by a series of indices to characterize the mixing behavior of air and the distribution of contaminants within a space [11]. Two indices are internationally accepted in the research area: contaminant removal effectiveness (CRE) and air change effectiveness (ACE).

Tracer gas techniques have been widely used to study the pattern of airflow and contaminant migration in order to measure ACE and CRE. A series of tracer gas tests using CH_4 were performed in in a study [12] to simulate contaminant migration and the removal of the contaminant generated by a point source in a residential building. The values of relative CRE and removal effectiveness were calculated from test results which can be used to assess air quality related problems in the building. Indoor air quality was evaluated using the CRE based on carbon dioxide (CO_2) concentrations for three schools equipped with displacement ventilation (DV) systems in Ref. [13]. In Ref. [14], CRE and local air change index was measured in order to characterize ventilation effectiveness in the occupied zone. CO_2 was used as the tracer gas to determine the CRE.

A literature survey shows that the common method of measuring the air quality indices is by means of a tracer gas technique. With the tracer gas method, the tracer gas, such as CO_2 and methane (CH_4), is injected into the room whose concentration is measured when the ventilation system is running to remove the contaminant.

The air quality indices theory may be applied in pharmaceutical cleanrooms, but particles are treated as the contaminant instead of tracer gases. However, since there is no correlation between gases and particles, the air quality indices, designed initially for tracer gas, need to be changed to fit the concept of particles. Only small particles (≥0.5 µm) should be used as they stay in the airflow.

Contaminant removal effectiveness (CRE) index

Calculations for the supply airflow rate should include a suitable CRE index, to ensure that the cleanroom will maintain the required conditions during most of the anticipated variations of the source strength [8]. The mixing of the supply air to a cleanroom and the cleanroom air is unlikely to be 100% perfect which will lead to the airborne concentration of contamination at some locations within a cleanroom is higher or lower than average. The CRE is a measure of the effectiveness of the cleanroom's air supply in diluting contamination in the cleanroom and can be used to calculate the extra air required to compensate for rooms with a poorer clean air supply.

Diffusers are used for mixing the supply air into the room air. They can be selected to give near-perfect mixing in the room, in which case contaminant removal is by dilution, or to direct clean air to the critical process locations. Different types of diffuser can result in different CREs with different values of throw and air patterns directed at those critical process locations.

One of the first indicators that define a perceived air quality is the CRE [15]. The CRE for

$$\varepsilon = \frac{C_e - C_s}{C - C_s} \approx \frac{C_e}{C} \qquad \text{Equation (1)}$$

where:

ε = Contaminant removal effectiveness index;

C_e = Particle concentration in the exit air (either in return or exhaust air);

C = Average particle concentration at critical points in the cleanroom;

C_s = Particle concentration in the supply air.

Two indoor air quality (IAQ) indicators, air exchange effectiveness and contaminant removal effectiveness, were studied in Ref. [16]. The results show that CRE provides more informative results for removal of contaminants with known positions and generation rates. In the original equation for CRE, the denominator of the equation is the average value of the particle concentration in the cleanroom. However, in the method described in this paper, there are only two particle counters in the cleanroom from which it is not possible to calculate the average particle concentration. They will, however, give the average concentration at the points where they are located, which are, presumably, critical locations where contaminant removal is required to be most effective. Therefore, in the equation for CRE, C has been redefined as 'Average particle concentration at critical points in the cleanroom'. The ventilation is effective when the concentration of contaminants at these critical points is low.

Air change effectiveness (ACE) index

Air change effectiveness (ACE) index has long been used to represent the ability of an air-distribution system to provide outside air where occupants breathe. It is a measure of how effectively the air present in a room is replaced by fresh air from the ventilation system [17]. It is defined in ASHRAE 129 [18] as the age of air that would occur throughout the space if the air was perfectly mixed, divided by the average age of air where occupants breathe. Thus, the ACE index is calculated by means of the following equation:

$$ACE = \frac{\tau_n}{2\tau_p} \qquad \text{Equation (2)}$$

where:

τ_n is the nominal time constant for the room, which is the reciprocal of the ACR;

$\overline{\tau_p}$ is the mean age of air at a particular point in the occupied zone.

Sandberg introduces the concept of the age of air in Ref. [19] which has been proven to be a useful tool in evaluating ventilation efficiency. The age of air is the length of time that some quantity of outside air has been in a building, zone, or space. The local mean age of air ($\overline{\tau_p}$) is defined as the average time it takes for air to travel from the inlet to any point p in the room.

The nominal time constant is defined as below:

$$\tau_n = \frac{V}{Q} \qquad \text{Equation (3)}$$

where:

V is the room volume;

Q is the air supply rate.

The mean age of air is calculated using the following equation:

$$\overline{\tau_p} = \frac{1}{C(0)} \int_0^{\infty} C_p(t)dt \qquad \text{Equation (4)}$$

where:

$C(0)$ is the initial concentration of the contaminant;

$C_p(t)$ is the concentration at a particular point in the room at time t.

For ACE in cleanrooms, it is not easy to measure the age of air with particles since particles cannot be used as the tracer. A gas can be the tracer because it can mix with a specified amount of the supplied air perfectly which makes that part of the air traceable when it flows through the cleanroom. A particle is solid so it cannot be mixed with the air perfectly. Thus, the ACE concept had to be modified to fit the use of particles.

W. Whyte et al redefined the ACE in Ref. [20] as below:

$$ACE = \frac{Air\ change\ rate\ at\ a\ location}{Average\ air\ change\ rate\ in\ the\ room} \qquad \text{Equation (5)}$$

The new formula of the ACE was derived in Ref. [20] from the original ACE formula for tracer gas [18] and the theory of recovery rate for particles [21]. W. Whyte et al indicated that the “air change rate at a location” could be measured by the “decay rate at a location”. And the decay rate can be calculated using the method described in Ref. [21].

The cleanliness recovery rate between two successive measurements is calculated from the following equation [21]:

$$n = -2.3 \times \frac{1}{t_1} log_{10}\left(\frac{C_1}{C_0}\right) \qquad \text{Equation (6)}$$

where:

n is the cleanliness recovery rate;

t_1 is the time elapsed between the first and second measurement;

C_0 is the initial concentration;

C_1 is the concentration after time $t_1 \; = C_0 \exp\left(-nt_1\right)$.

Air change rate (ACR) is defined in Ref. [21] as the "rate of air exchange expressed as number of air changes per unit of time and calculated by dividing the volume of air delivered in the unit of time by the volume of the cleanroom or clean zone". With this definition of ACR, the calculation of ACR requires a known volume. However, with the "air change rate at a location", there is no known volume. For this reason, "air change rate at a location" should be replaced with "recovery rate at a location" in Equation (5) as that is what is measured in Ref. [14]. However, if "recovery rate at a location" is the numerator in the ACE equation, the denominator should be the average recovery rate so that the numerator and the denominator are in the same units. In fact, with perfect air mixing, the recovery rate for the room can be demonstrated to be the same as the air change rate in the room [22]. Therefore the "air change rate in the room" can be used as the denominator in the ACE equation and there is no need to attempt to measure the recovery rate at different points in the room in order to obtain the average recovery rate.

Thus, the ACE can be redefined as below:

$$ACE = \frac{Recovery\ rate\ at\ a\ location}{Air\ change\ rate\ in\ the\ room} \qquad \text{Equation (7)}$$

The ACR is defined by the following expression:

$$ACR = \frac{Q}{V} \qquad \text{Equation (8)}$$

where:

Q is the supply airflow rate;

V is the room volume.

To calculate the ACE at a particular location in a cleanroom using ACE=$Recovery\ rate\ at\ a\ location$⍰$Air\ change\ rate\ in\ the\ room$⍰ Equation (7), the denominator is the ACR in the room calculated by Equation (8) and the numerator is calculated by n=−2.3×$\frac{1}{t_1} log_{10}\left(\frac{C_1}{C_0}\right)$ Equation (6). An ACE value of less than 1 indicates that the recovery rate at that location is less than the average recovery rate. At some locations, the

ACE value could be greater than 1, which demonstrate that the air distribution at those locations provides a faster recovery rate than the air change rate.

Dispersion rate of particles

The sources of airborne particle contamination in cleanrooms are machinery and personnel, and the total dispersion rate is calculated as follows:

$$Total\ dispersion\ rate = Dispersion\ rate\ per\ person \times No.of\ personnel + Dispersion\ rate\ from\ machinery$$ Equation (9)

The particle shedding experiments shown in Ref. [29] present the number of particles shed per minute by test subjects in personal clothing as shown in Table 1. The tests were carried out in a body box.

There will also be some re-dispersion from the floor during walking, but in a typical cleanroom, it is less than 1% [23]. Typical dispersion rates are shown in [24], [25] and [26]. The contamination index for various personnel activities ranges from 100,000 particles per minute to 30,000,000 particles per minutes of 0.3m in size and larger according to different levels of actions [27]. Ref. [28] gives an indication of particulates generated by personnel within a cleanroom as shown in

Figure 1.

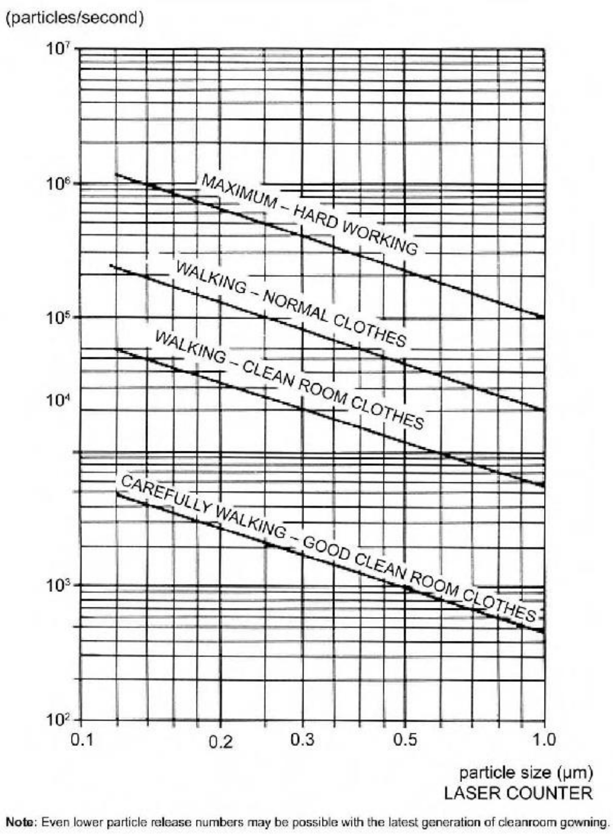

Figure 1: Number of particles generated per second per person.

The particle shedding experiments shown in Ref. [29] present the number of particles shed per minute by test subjects in personal clothing as shown in Table 1. The tests were carried out in a body box.

Table 1: Number of particles shed per minute by test subjects in personal clothing [29].

Test-person	Sex	Average number of particles/minute[1]	Average number of particles/minute[1]	Average number of particles/minute[1]	Average number of particles/minute[1]
		standing	**walking**	**standing**	**walking**
	M/F	**≥0.5μm**	**≥0.5μm**	**≥5μm**	**≥5μm**
1	*M*	268	4,650	3	61
2	*F*	65	1,460	2	49
3	*M*	184	4,398	5	100
4	*F*	113	2,179	8	52
5	*F*	182	2,287	18	67
6	*F*	346	5,547	7	112
7	*M*	404	13,367	10	316
8	*F*	189	3,895	1	35
9	*M*	154	2,626	5	76
10	*F*	58	798	6	33
11	*F*	53	657	6	30
12	*F*	13	1,998	0	92
13	*M*	337	4,784	32	209
Average on all measurements		182	3,742	8	95

Actual numbers of particles (projected) [2]	86,007	1,768,346	3,781	44,785
Notes: [1] As measured by the particle counters in the body box in which the tests were conducted [2] Adjusted to take into account the ratio of the airflow through the particle counters to the total airflow through the body box				

Dispersion rate of particles from personnel in a cleanroom

The dispersion of particles from personnel is usually the most important source in the cleanroom. To determine the exact value of the dispersion rate is difficult, as the rate of particle dispersion is dependent on each person, the design of the cleanroom garments, the occlusive nature of the fabrics used to manufacture garments, and the activity of personnel [8]. It is clear from dispersion chamber experiments presented in Ref. [30] that the dispersion of contamination from personnel varies according to activity and clothing.

Dispersion rate of particles generated by machinery and equipment

Dispersion rates of particles from machinery and other equipment vary according to type, and it is best to obtain information about the dispersion rate from the manufacturer of the machinery or equipment. Alternatively, the total dispersion rate can be obtained experimentally using the method outlined in ISO 14644-14 [31]. This method can also be used to include personnel operating the machinery, so that the total dispersion rate of all sources in the cleanroom obtained.

Ventilation equations for ACR calculation

The greatest effect on the particle concentration in non-unidirectional airflow cleanrooms is from the supply airflow rate and dispersion rates from personnel and machinery. The derivation and application of the 'ventilation equations' can be obtained in building services textbooks such as Ref. [32] and Ref. [33]. These equations are normally used to determine the concentration of undesirable or toxic gases during the build-up, steady state, and decay, in ventilated rooms or buildings. Equations used to calculate the airborne concentration of particles and microbe-carrying particles (MCPs) in the build-up, steady-state and decay conditions in non-unidirectional cleanrooms have been discussed by W. Whyte et al [34] [30].

The equation for an estimate of the concentration of airborne particles is proposed in Ref. [8]. By rearranging this equation in Ref. [30], the air supply rate for a given concentration of small particles can be calculated.

$$Q = \frac{D}{C} \qquad \text{Equation (10)}$$

where:

Q = Supply airflow rate (m^3/s);

D = Total particle dispersion rate from personnel and machinery (counts/s);

C = Required airborne particle concentration ($counts/m^3$) in the considered location.

d.

$Q=\frac{D}{C}$ Equation (10) is based on the condition of particle "perfect mixing" with room air which rarely occurs in actual cleanrooms. Therefore, the air quality index is used to include the factors of "actual mixing" condition and the effectiveness of various airflow patterns. Thus, the ventilation equation can be derived as:

$$Q = \frac{D}{\varepsilon C} \qquad \text{Equation (11)}$$

where:

ε = the air quality index (CRE or ACE).

Both C and D should refer to the same occupancy state, and to the specified particle size under consideration. If an air change rate is required, it can be calculated from the cleanroom's physical volume as follows:

$$ACR = \frac{3600D}{\varepsilon CV} \qquad \text{Equation (12)}$$

where:

ACR = Air change rate per hour;

V = Cleanroom volume (m^3).

The emission data given in [24], [25] and [34] should be used to estimate the contamination source strength depending on the number of personnel, the clothing to be used and the process equipment. $Q=D\varepsilon C$ Equation (11) can then be used to estimate the minimum supply airflow rate required. The calculations should only be used as a guide and should include any required compensating factors. The designer should determine the current contamination source strengths for existing cleanrooms and estimate all potential contamination source strengths for new cleanroom builds. Sufficient flexibility should be built into the design to allow progressive airflow tuning to take place as shown in Figure 2.

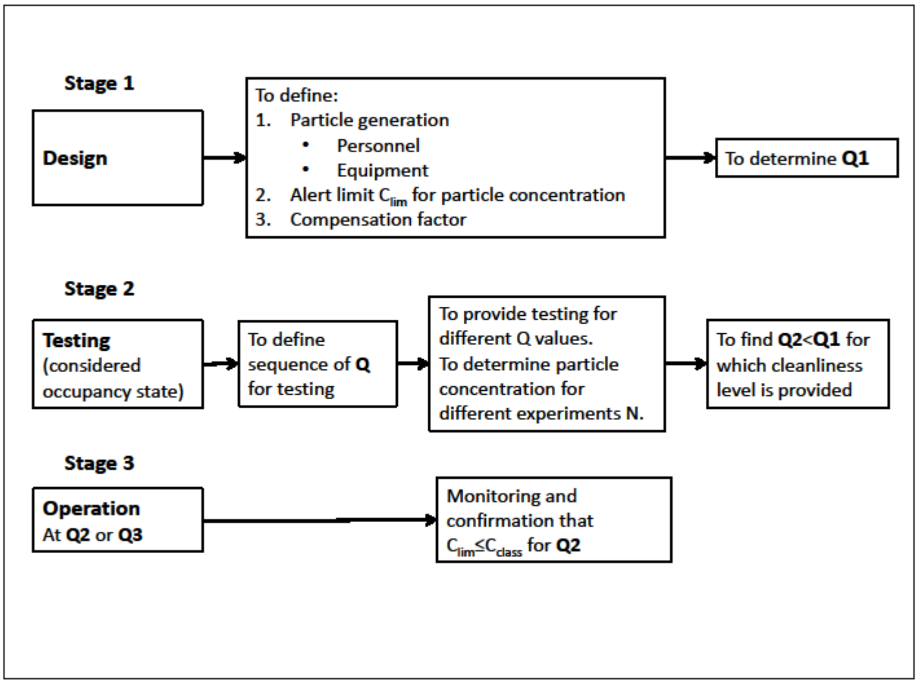

Figure 2: Design-testing-operation [8], Q1 is the design, airflow rate, Q2 is the airflow rate determined by testing and Q3 is the operational airflow rate if this is different from Q2.

Ref. [7] provides discussion, guidance, and examples on the use of ICH Q9 “Quality Risk Management (QRM)” when reducing HVAC ACRs within manufacturing and supporting operations. As defined in Ref. [35], QRM is “a systematic process for the assessment, control, communication, and review of risks to the quality of the drug (medicinal) product across the product lifecycle”. Ref. [7] demonstrates that a reduction in airflows or ACR only can be considered if an appropriate QRM is conducted and approved. Use of the QRM approach provides an effective method to ensure the requirements from all stakeholders in the process are identified and assessed.

Conclusion

This first part of the paper has introduced the air quality indices, CRE and ACE, and demonstrated how they have been developed for use with particles rather than tracer gases. The theory of the dispersion rate of particles has been discussed and the measured values from other papers have been shown. The ventilation equations for ACR calculation have been developed with the introduction of the air quality indices based on particles. The second part of the paper, to be published later, will describe the experiments carried out to research these equations and present the results.

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